Pedestrian injury severity in the event of a collision with a truck: are energy absorbing adaptive deformable fronts suitable?

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Abstract: It is well known that adaptive deformable fronts attached to trucks reduce pedestrian injury. However, the suitability of these frontal attachment devices from a holistic point of view, considering both primary and secondary impacts, is questioned in this paper. Using head-injury-criteria index, the effects of pedestrian gait and different closing speeds are considered for evaluation of numerous truck-pedestrian side and rear impact situations. Numerical simulations, considering coupled rigid and deformable-body dynamics, have been carried out in this paper to arrive at conclusions. For primary side impact scenario DEA frontal attachment provides a performance improvement specifically for 0% gait; however, the performance improvement is non-uniform for other gait cycles. For primary rear impact scenarios, it is observed that DEA is not a useful alternative at all. For secondary collision scenarios (involving both side and rear impacts) DEA is not at all an effective means for performance improvement.

Keywords: pedestrian-truck collision; adaptive deformable fronts; primary and secondary impact; pedestrian gait.

1 Introduction

A sizeable portion of the fatal pedestrian crashes in India involve a truck as the major impacting vehicle (Mitra et al., 2012; Mohan, 2001). It is important to note that the mechanics of impact of a pedestrian in the event of a truck-pedestrian collision is

significantly different in comparison to a collision between a car and a pedestrian (Chawla et al., 2000; Feist et al., 2008). In case of a pedestrian-car accident, the lower extremities are hit first and the remaining body sections later, whereas in a truck-pedestrian collision, nearly all the body parts of the pedestrian are hit simultaneously. Such collisions tend to result in higher injury severities, even leading to death (Chawla et al., 2000; Fildes et al., 2004; Kajzer et al., 1992; Longhitano et al., 2005), due to the fact that the head of the victim is involved in the very first stage, resulting in higher severities or fatalities.

In the event of a collision, there are primarily two different types of injuries sustained by the pedestrian. Typically, at first when the pedestrian comes in contact with the vehicle, he/she sustains a primary injury, and after that when the pedestrian falls on the road, he/she sustains a secondary injury. In both cases, pedestrian-vehicle interaction and pedestrian-road surface interaction can result in very high biomechanical injuries (Feist et al., 2008). While most of the vehicle-pedestrian collisions terminate in pedestrian contacting the ground (Simms and Wood, 2009) and resulting in significant injuries from secondary impact, insufficient research has addressed the secondary impact of a pedestrian till date. Some researchers (Meinecke et al., 2003; Rosen et al., 2010) prescribe that the effective means of reducing injury from secondary impact is by reducing the speed of the vehicle on the application of brakes prior to a collision. Typically, these researchers have utilised an assembled dataset and arrived at their conclusion by using probabilistic methods. However, a detailed analysis involving the kinematics of the passenger in a reconstructed truck-pedestrian collision scenario, and estimating the biomechanical injury severities (both primary and secondary) sustained by the pedestrian has not yet been presented in existing literature, which this study addresses. In this regard, it is important to mention that for pedestrians' secondary impact scenarios, ground contact injuries are the primary determinants of injuries, and that Otte and Pohlemann (2001) and Taneda et al. (1973) expressed that the head impact largely determines the overall severity compared to pelvis fracture, thorax and abdomen injuries. It has also been reported by Feist et al. (2009) that injuries sustained by pedestrians in truck-pedestrian collision are primarily the head region (with 37% of all injuries), followed by lower extremities (21%), the thorax (12%), and the abdominal or pelvic area (12%). On the other hand, injuries sustained by the pedestrians in passenger car collisions (Yang, 2005) are primarily the lower extremities (with 32.4% of all injuries), followed by the head region (26%), the abdominal/pelvic area (12%), and the thorax (5.5%). Hence, for comparison of injury severity in case of truck-pedestrian collision HIC could be selected as the major injury criteria and has been used in this manuscript to arrive at conclusions.

For reducing the impact severity in the event of a truck-pedestrian collision, different Retrofittable Energy Absorbing Front-Protection Systems (REAFPS) for a truck have been prescribed (Feist et al., 2008). These REAFPS include adaptive deformable front (ADF), multi-chambered net of pneumatic tubes (MCNT), segmented energy absorbing front, plastic steel safety bar, foam-steel safety bar. In all these cases it has been shown (Feist et al., 2008) that the primary impact severity to the pedestrian has been reduced significantly. Further, it was also concluded (Feist et al., 2008) that these energy absorbing front-end devices could achieve a reduction of 90% Head Injury Criteria (HIC). However, the effectiveness of these systems on secondary impact was not investigated, even though the need for such research to gain an understanding of the overall efficiency of these devices was highlighted by the authors (Feist et al., 2008).

In the connection of pedestrian-vehicle impact, Simms and Wood (2009) concluded that the severity of the pedestrian-vehicle and pedestrian-ground impacts is dependent on both impact speed as well as the vehicle design characteristics. Further, the authors (Simms and Wood, 2009) also stated that the pedestrian impact kinematics is dependent on the principal line of vehicle impact force with respect to the pedestrian's centre of gravity. As a result, injury severity will vary with the type of vehicle, the speed of impact as well as the height of the pedestrian. Additionally, there is also some evidence that the walking posture of the pedestrian influences kinematics and injury outcomes (Feist et al., 2009, McLean and Anderson, 1997; Untaroiu et al., 2009). In a recent study (Peng et al., 2012), it has been concluded that vehicle-impact velocity, as well as pedestrian gait, strongly influences the head-impact condition. It has also been mentioned by the authors (Peng et al., 2012) that the head-impact angle depends on the vehicle-front geometry and pedestrian gait. Further, the study revealed that the head-impact orientation at the time of contact with the vehicle is mainly influenced by the pedestrian gait (Peng et al., 2012). While very relevant, the study focused on the passenger cars and primary impact scenarios – which is different from the focus of the current study. In this background, the objective of this study is to present a comprehensive assessment of the suitability of ADF's for the safety of a pedestrian involved in a collision (both side and rear impact cases) with a truck from a combined viewpoint of primary and secondary impact scenarios. The study also investigates the effect of pedestrian gait postures in the truck-pedestrian collision scenario. In the following section, the methodology followed in this study was described first, followed by results and conclusions.

2 Methodology

The methodological approach adopted in this study can be divided into two broad steps, a) development of the numerical model of truck-pedestrian impact and b) validation of the model component. In the following section, the methods are given in detail.

2.1 Development of numerical model

The truck has been modelled as a parameterisable rigid multi-body vehicle in commercial software MADYMO (MADYMO, 2009). Tata SE 1613 Turbo EX BS II, commonly seen on Indian highways, has been selected as the model for the truck. The geometry, gross weight of the vehicle, front and rear axles' weights are obtained from the vehicle brochures supplied by manufacturers. In Table A1, GVW represents Gross Vehicle weight, GCW represents Gross Combined weight, FAW and RAW represents Front and Rear Axle Weights. The truck model consists of eight major rigid bodies: truck, bumper, front axle, rear axle, front left wheel, front right wheel, rear left wheel, rear right wheel. Data of the force-penetration curves for different components are taken from various previous literature such as Chawla et al. (2000) for the front grill in the truck and Ramli and Yamazaki (2012) for the bumpers. Truck rigid body is attached to the reference space by a translational joint which facilitates truck movement in the X direction only. The front axle and the rear axle are connected to the centre of gravity (c.g.) of the truck body through a rigid joint. Both the front tyres and both the rear tyres are attached to the front and rear axle respectively by revolute joints to facilitate the tyres to revolve around Y-axis and move in the XZ plane. The bumper of the truck is attached to the truck body

by one directional translational joint to facilitate movement in X direction. The front grill of the truck along with the cabin and windshield is attached to the c.g. of the truck body. All of these surfaces are ellipsoid surfaces. Tyres are modelled as cylindrical surfaces, and they are attached to the wheels. Contacts between the road and the tyres of the truck are defined using the default values of the tyre model in MADYMO. Tata SE 1613 Turbo EX BS II truck and the finished truck model in MADYMO are shown in Figure A1 whereas Table A1 shows the dimensions and weights of the truck parts.

The pedestrian model, selected from MADYMO is a Hybrid III 50th percentile mid-sized male for both side and rear impact studies. The Hybrid III 50th percentile mid-sized male model in MADYMO has been developed based on anthropometric data from the European population. Thereby there is a limitation in the study since anthropometric specifications for average Indian male are somewhat different in comparison to a European counterpart. The total mass and standing height of the model (as reported in Madymo manuals) is 75.5 kg and 1.74 m respectively.

The current study also considers the effect of different gait cycles for the pedestrians. A gait cycle has been characterised as a specific posture of the pedestrian during walking and is defined using the angles of lower and upper extremity joints. The starting point of the gait cycle is considered as the stance corresponding to the initial contact of the right foot with the ground (Perry and Burnfield, 2010). Details about pedestrian gait cycles can be obtained from previous literature (Perry and Burnfield, 2010; Apkarian et al., 1989; Untaroiu et al., 2009). It is well known that the three major joints of the foot, namely, the subtalar, midtarsal and metatarsophalangeal joints, play a significant role during human walking. Since these joints are lacking explicitly in the pedestrian foot model in MADYMO, the data for the joint angles and other necessary information (such as the speed with which the pedestrian is traveling which has been taken as 1.18 m/sec) for simulating gait cycle in the pedestrian model have been taken from Perry and Burnfield (2010), Apkarian et al. (1989) and Untaroiu et al. (2009). Illustrative diagrams showing the gait cycle (in percentages) as considered in this manuscript is shown in Figure A2.

The roadway is modelled as a plane surface with a stiffness of 1600 MPa and Poisson's ratio of 0.35 (as per Feist et al., 2009). Data of the force deflection curve representing the contact interaction of the road surface with the pedestrian is also obtained from Feist et al. (2009).

The deformable energy absorbing (DEA) device fitted to the front of the truck is chosen to be made up of semi-rigid closed-cell poly-vinyl-chloride foam having a density of 100 kg/m^3 and a thickness of 100 mm. Since it is expected that the DEA device will compress and absorb the energy imparted in an accident, the modelling of the DEA device has been done in ABAQUS. It should be mentioned at this point that the DEA device modelled in ABAQUS has been integrated with other parts of the model built using rigid body dynamics software MADYMO. The stress-strain characteristics of the foam material can be obtained in details from Mitra (2010) and Mitra and Raja (2012). In this regard, it should also be noted that the compression characteristic of foams resulting in energy absorption have been shown by previous researchers (Ghoshal and Mitra, 2014). The DEA system consists of an upper grill and bumper parts, and sufficient gap space is left for the headlights and engine grill for air circulation and lighting. The clearance gap kept in between the DEA system and body of the truck bumper is 100 mm. The DEA frontal system consists of two parts, one attached to the front of the truck body and another portion attached to the bumper. These two parts are considered since the

front of the bumper is not flush with the front of the truck body but has a thickness of 10 mm which is added to the front of the truck body. Springs with the stiffness of 106 MPa, (which are attached to the truck body and the bumper) are connected to the DEA system with one-dimensional translational joints allowing motion only along the X-direction. Truck attached with DEA frontal system modelled with ABAQUS and integrated with other rigid body parts modelled with MADYMO, is shown in Figure A3.

Two different types of accident scenarios have been investigated in this study: 1) Truck-Pedestrian Side Impact; 2) Truck-Pedestrian Rear Impact. The injury severity in primary and secondary collision events has been investigated for the above-mentioned collision scenarios considering trucks attached with or without a frontal DEA device.

The truck speed has been varied between 15 to 40 km/hr at an increment of 5 km/hr. The initial velocity of the pedestrian has been taken as 4.2 km/hr (1.18 m/s). As per the recommendation (Feist et al., 2009), the coefficient of friction between the pedestrian and surfaces of the truck and/or DEA is taken as 0.2, whereas the value taken in between the ground and the pedestrian or truck wheels is taken as 0.5.

2.2 Model component validation

To perform rigorous experimental validations for the numerical model, one should consider a live person being subjected to an accident scenario as simulated in here. However, that kind of study is unrealistic. The next best possible experimental verification can be done through instrumented dummies being subjected to the accident scenario described in this work. It should be noted that there is a difference between the use of a live model and that of an instrumented dummy since the dummy does not have any reflex action which is usually possessed by a living person. It can also be argued that the issue of reflex action is also absent for numerical models and thereby instrumented dummy research might give good validation of the numerical results even though the results might differ from real situations. However, it should be noted that financial constraints prevented us from carrying out experimental investigations using instrumented dummies.

Instead, all the individual model components used in the study have been validated against available experimental research and/or available experimental investigations. The acceleration of the head obtained from numerical simulation results has been compared to that of experimental investigations (Feist et al., 2008). However, it should be noted that unless the two systems being compared have exactly same characteristics with regards to shape, impact distance and/or velocity the entire acceleration time history will not match, but the resultant peak accelerations of the two systems with same mass will match. In Feist et al. (2008), an experimental investigation has been conducted wherein a hemispherical head-form impactor is impacted with a cylindrical/rectangular specimen at a velocity of 11 m/s (approx 40 km/hr). The value of the maximum acceleration recorded is 170 g for the case when the cylindrical specimen is a high-density polypropylene tube with steel inlay (refer Figure 15 in Feist et al., 2008); whereas a value of 350 g is recorded for the case in which the rectangular specimen is of EPP foam (refer Figure 18 in Feist et al., 2008). The weight of the hemispherical head-form utilised in the experiment is 4.8 kg which is comparable to the weight of the head region in the models in MADYMO. A polypropylene tube with a steel inlay is roughly similar to a filled steel tube which in turn approximates the material being utilised for the truck body. A peak value of 160 g head acceleration of the pedestrian is obtained from the numerical

simulations carried out in this paper for the case of side impact at a closing speed of 40 km/hr without DEA frontal attachment. On the other hand, PVC foam has been utilised in the current study which is comparable to EPP foam used in the experimental investigation. A peak value of 320 g head acceleration of the pedestrian is obtained from the numerical simulation carried out in this study for the case with DEA side impact at a closing speed of 40 km/hr with DEA frontal attachment. This comparison of reported experimental investigation data and data obtained from numerical simulation validates the numerical model for the case of primary side impact scenario. It should be noted here that there are no reported experimental and/or previous numerical investigation for rear end primary impacts and thereby could not be validated in our study.

Apart from validations with experimental results with headforms, validation of primary impact has also been carried out against previously published numerical results (Chawla et al., 2000). Figure 1 shows a good correlation between the results of the primary side impact without DEA obtained from the numerical model in this study along with previous numerical results (Chawla et al., 2000). The slight difference in results can be attributed to the difference in the pedestrian model used in Chawla et al. (2000) and the current study. Chawla et al. (2000) considered pedestrian models based on Indian population (by applying scaling factors to models in MADYMO developed as per European population) whose anthropomorphic details are different from the European standards as taken in this study. With regards to validation of the model for secondary impact, experiments have been carried out with real dummy models as mentioned in literature (Feist et al., 2009, p.12) and it has been reported that the peak head acceleration in case of rear impact at closing speed of 30 km/hr is around 1170 g. Similar numerical investigations are carried out in our study, and the value of 1206 g has been obtained, which shows an acceptable match with the experimental results. There have been no reported experimental investigations of secondary side impacts and thereby those situations could not be validated.

Figure 1   Comparison of HIC values in primary collision
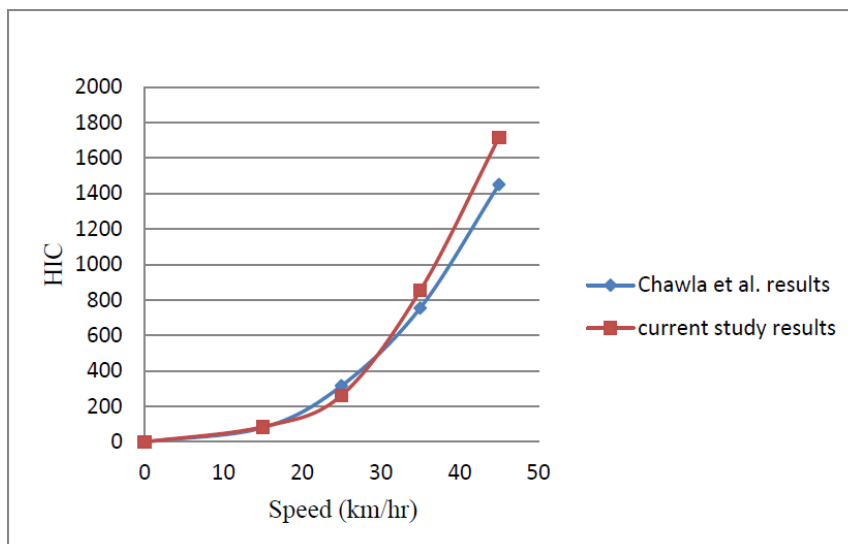
3 Results and discussion

In the following sections, results obtained from truck pedestrian side impact are presented and discussed first followed by truck pedestrian rear impact.

3.1 Truck pedestrian side impact analysis

The simulation of the truck pedestrian side impact with and without DEA is shown in Figure A4. It is observed that for side impact the pedestrians take a longer time to touch the ground after primary impact with trucks attached with DEA frontal system in comparison to trucks without DEA frontal attachments – which might be one of the major factors behind the reduced injury in some instances (based on gait cycle and speed). Energy absorption of the DEA frontal system is responsible for the pedestrians taking more time to touch the ground after impact compared to without DEA systems. From first principles of physics it can be explained that in the case of a contact between two bodies, the energy absorption increases with the increase in the time of contact. Since DEA materials such as foam have a lower stiffness than steel utilised for the truck front panels, it absorbs energy by deformation and thereby reduces energy transfer to pedestrians. However, it should also be noted that the stiffness of the DEA utilised should be slightly more than the stiffness of the human body for the material (as has been done in this study as well as in other previous research studies) to represent an ideal choice for a DEA device.

While the effectiveness of DEA in primary impact is known to the research community, the main issues of focus in this study are injury severity from a comprehensive and cumulative primary and secondary impact scenario, and the influence of pedestrian posture at the time of impact through different gait cycle (which has been shown in Figure A2). Table 1 shows a variation of pedestrian HIC values with various impact speeds as well as gait during the primary impact of the pedestrian with a truck for cases with and without DEA, whereas Table 3 shows the same attributes in a secondary impact. In both tables, injury severities for various gait cycles are shown. It should be noted that typically a tolerance level of 1000 for the Head Injury Criteria (HIC) is considered which is equivalent to a 14% probability of an AIS4 (life-threatening) head or brain injury; whereas tolerance level of 1860 for HIC signifies non-survivable fatal injury (Feist et al., 2009).

Table 1 HIC with various speeds for truck-pedestrian side impact scenario (primary impact)

Speed (km/hr)	*Primary side impact HIC*									
	Without DEA (different gait cycle percentages)					*With DEA (different gait cycle percentages)*				
	0%	*10%*	*20%*	*30%*	*40%*	*0%*	*10%*	*20%*	*30%*	*40%*
15	65	28	30	33	32	1	3	3	2	2
20	131	147	158	173	166	2	9	6	4	4
25	343	371	394	429	415	6	325	245	133	78
30	686	721	746	787	762	638	805	804	492	445
35	1154	1185	1222	1280	1236	749	1450	1480	1264	1046
40	1784	1803	1846	1896	1852	1342	2215	2401	1896	2291

From Table 1 data it can be observed that up to 30 km/hr impact speed, the pedestrian will witness non-life threatening head injuries (since the HIC values are below 1000). This observation is valid for both with and without DEA situations. At around 35 km/hr the pedestrian will suffer life-threatening head injury situations for all cases of different gaits and both with and without DEA, except for 0% gait with DEA. At 40 km/hr irrespective of gait or presence of DEA, the pedestrian will witness life-threatening situations which are near to fatal situations. It can also be observed from Table 1 that HIC increases with increasing vehicle speed for all gaits in primary impact, but there is considerable variation in HIC across various gaits for a particular impact speed. The table shows that with 0% gait there is an improvement in pedestrian performance with DEA frontal attachments (at 35 km/hr HIC values are below 1000 and for 40 km/hr HIC values are significantly below 1860 for the case with DEA compared to cases without DEA), which in fact matches with the observations (Feist et al. 2008). However, it should also be noted that this improvement in performance is not uniform over all other pedestrian gait cycles – clearly indicating the influence of pedestrian posture (an artefact of pedestrian stability) on pedestrian kinematics and injury severity. Additionally, it can also be stated that even while advantage may be gained with DEA for a specific gait cycle, over a whole range of gait cycles, the gain in performance is rather questionable.

Figure 2   HIC vs. gait for various speeds for truck-pedestrian side impact (primary impact without DEA)
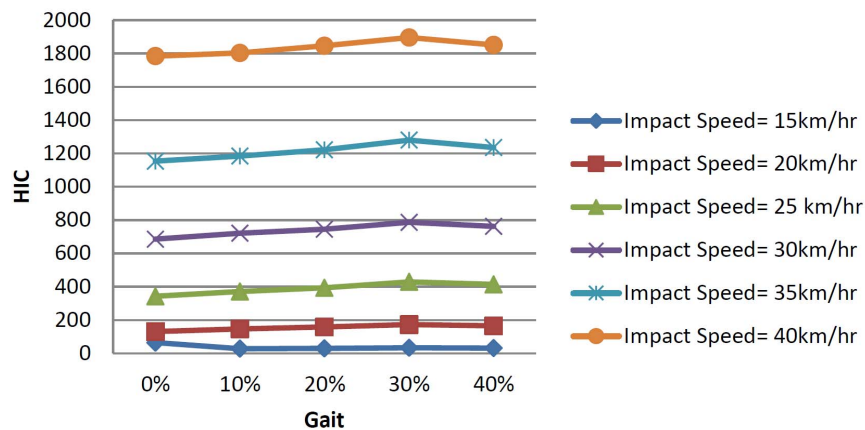

Figure 2 shows that HICs in primary impact without DEA at various gaits in various impact speeds follow a definite pattern – an observation similar to that reported by previous researchers (Elliot et al., 2012). A positive slope in HIC index is observed from 0 to 30% gait cycle followed by a decrease, which indicates that 0% gait (which is typically considered in researches (Feist et al., 2008) and others) will yield the lowest values of HIC compared to other gaits in the cycles. No specific clear trend could be observed in Figure 3 which deals with HICs in primary impact with DEA at various gaits in various impact speeds. However, one observation could be made that 0% gait represented the most stable posture for a pedestrian indicated by lower HIC values over other gaits at the same impact speed. When attached with DEA, a sudden increase in HIC values are also observed from 0% to 20% gait indicating that 20% gait may be the most

unstable posture for a pedestrian. Based on the results from primary impact at various gait cycles, the benefits of DEA are apprehensible. The findings from this research indicate that a more comprehensive and holistic approach towards this problem should be envisioned before statements could be made with regards to the suitability of DEA frontal system for improving pedestrian safety in the event of truck-pedestrian side-impact. Further, findings show that there is still scope for more experimental research in this area.

Figure 3 HIC vs. gait for various speeds for truck-pedestrian side impact (primary impact with DEA)
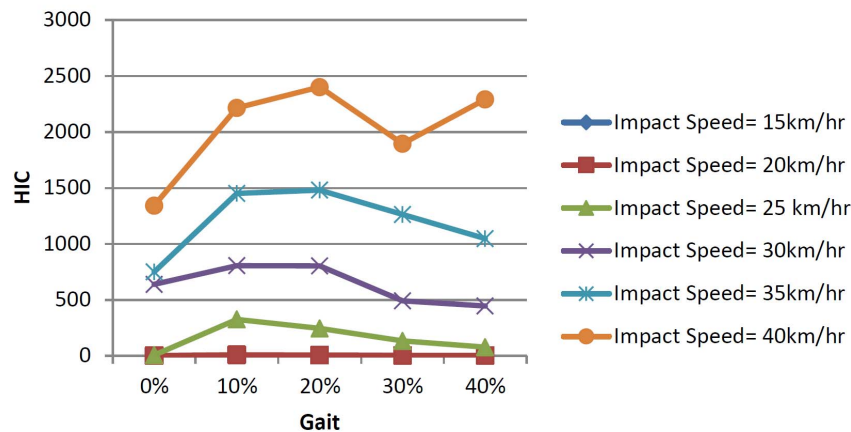
The HIC values in Table 2 are significantly higher than 1860, with some values even reaching around 25,000 which is 30 times higher than the standard specified in Federal Motor Vehicle Safety Standard (FMVSS) 208. It should be noted that FMVSS 208 is developed for automotive occupant crash protection scenario which is significantly different compared to that of a pedestrian subjected to a collision with that of a truck. Thereby the standards cannot be at all applied to that of the pedestrian-truck accident situation. In an automobile, the occupant is enclosed within a confined space, where the materials around the occupant are not of high stiffness and strength compared to that of the pavement material. It should also be realised that the free flight distance covered by the pedestrian head is significantly large for a pedestrian subjected to an accident with a truck compared to that of an automobile occupant involved in an accident. Thereby the large values as obtained from the simulations in Table 2 are not completely unrealistic.

It is apparent from HIC values in secondary side-impact situations (refer Table 2), that DEA frontal attachments do not bring down injury severity within survivable limits (below a value of 1860) for pedestrians when they impact with the ground. Additionally, it is also observed that the injury severities from secondary impact for both impact scenarios i.e. with and without DEA do not follow similar definable patterns as that of primary impact. There is clear indication that the injury severities in secondary impact are significantly higher than any tolerable limit – a finding never reported in any previous studies thereby raising concern about the effectiveness of DEA from a holistic safety point of view; since pedestrians will not be able to survive anyways after they hit the ground. This finding also emphasises further investigation of pedestrians in secondary

impact – an important impact scenario which has received a lot of attention in case of the safety of motorised vehicles passengers, but not so much for non-motorised road users.

Table 2   HIC with various speeds for truck-pedestrian side impact scenario (secondary impact)

	Secondary side impact HIC									
Speed (km/hr)	*Without DEA (different gait cycle percentages)*					*With DEA (different gait cycle percentages)*				
	0%	*10%*	*20%*	*30%*	*40%*	*0%*	*10%*	*20%*	*30%*	*40%*
15	13341	8841	13623	6872	13458	5198	10285	3421	8363	9998
20	9224	9961	16341	18508	14067	9731	10700	7633	2509	2086
25	8669	11506	20321	19945	12815	9759	11202	4216	11822	14795
30	6095	3738	8906	5280	9700	10124	9915	7092	16440	15157
35	9729	5281	9217	5824	12543	13070	17367	12184	14749	16015
40	14200	9492	11895	8163	14428	16538	27952	19355	16366	20164

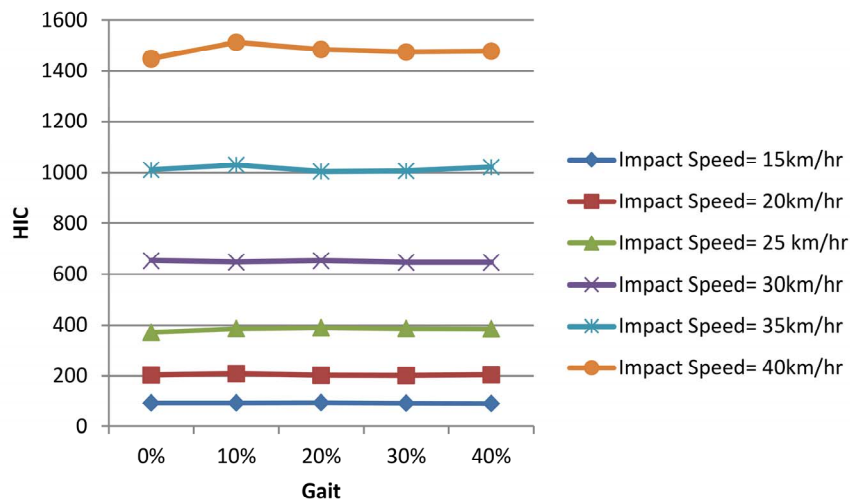## 3.2   Truck-pedestrian rear impact analysis

The impact kinematics (refer Figure A5) is observed to be quite different for the two scenarios (with and without DEA) – in trucks without DEA the pedestrian falls sidewise on the ground whereas, in case of trucks with DEA, the pedestrian falls straight with face down resulting in the head to come in direct contact with the ground. As a result, almost no benefit is gained from the DEA system for the rear-impact scenario. It should also be realised that the impact kinematics of the head in a side impact situation is significantly different from that of a rear impact situation. In a side impact situation, the truck front first comes in contact with the side of the pedestrian body and not directly with the head which is the case for a rear impact scenario. From Table 3 it can be observed that in the primary impact scenario, without DEA case (with all different gaits) has no life-threatening head injury situation at or below 30 km/hr impact. However, such a generalised statement cannot be made in the case of trucks with DEA. It is observed that only for gait cycles 10 – 30%, pedestrians sustain no life-threatening head injury at or below 20 km/hr impact. For without DEA cases, the head on contact with the hard steel front of the truck undergoes a rotation due to which eventually the pedestrian falls sidewise; however, in the case of with DEA the time of contact of the head with the truck front is increased due to the presence of the comparatively soft DEA layer which eventually results in higher primary impact HIC values and also influences the kinematics of the pedestrian due to which he/she falls with face down. It could be noted that better results are obtained for certain gait positions with DEA case, which can be explained by the inherent stability of the person in such gait postures. Overall, based on the results shown in Table 3, it can be inferred that DEA does more harm than help in pedestrian in rear impact collisions. It is also observed that in a rear impact, the effect of gait is significantly different in primary and secondary collision events.

Table 3 HIC with various speeds for truck-pedestrian rear impact scenario (primary impact)

Speed (km/hr)	*Primary side impact HIC*									
	Without DEA (different gait cycle percentages)					*With DEA (different gait cycle percentages)*				
	0%	10%	20%	30%	40%	0%	10%	20%	30%	40%
15	93	93	94	92	91	1234	45	366	280	1134
20	204	209	203	202	205	3167	866	818	636	2581
25	372	386	390	386	385	6037	1695	1517	1198	4722
30	653	647	652	646	646	10651	2986	2754	2107	7558
35	1012	1031	1005	1008	1023	16561	4672	4069	3270	12151
40	1448	1513	1484	1475	1478	24754	7010	5943	5150	18233

Figure 4 shows that there is no effect of gait in primary rear impact scenarios for cases without DEA frontal attachments. This observation is quite different from observations in a side-impact situation as shown in Figure 2. In secondary impact even though the values of HIC are very high for the case with DEA, Figure 5 shows a trend in which lowest HIC values were observed for gait cycle at 30% for all speeds in comparison to gait cycles at 0 and 40%. The stability of different gait postures may explain this trend.

Figure 4 HIC vs. gait for various speeds for truck-pedestrian rear impact (primary impact without DEA)

Figure 5   HIC vs. gait for various speeds for truck-pedestrian rear impact (primary impact with DEA)
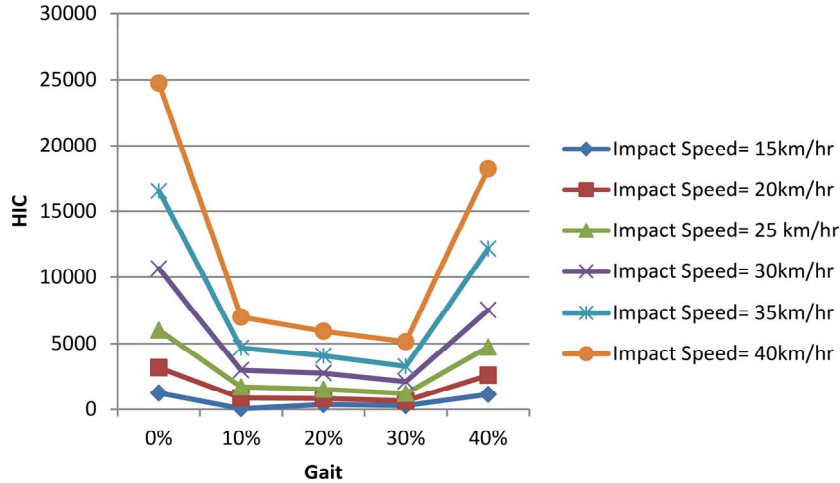

Table 4 shows the variation in HIC by a pedestrian in secondary rear impacts with the change in speed. It may be noted that for rear-end secondary impact scenarios for all speeds and all gaits, head injury exceeds allowable limits for trucks even at low speeds with or without DEA frontal attachments. From the above observations, it may thus be concluded that energy absorbing frontal attachment is not effective in pedestrian rear impact with trucks as it is unable to reduce the severity of impact in a secondary impact.

Table 4   HIC with various speeds for truck-pedestrian rear impact scenario (secondary impact)

	Secondary side impact HIC									
Speed (km/hr)	Without DEA (different gait cycle percentages)					With DEA (different gait cycle percentages)				
	0%	*10%*	*20%*	*30%*	*40%*	*0%*	*10%*	*20%*	*30%*	*40%*
15	13332	5576	14735	18907	24652	4213	4054	13358	10712	4643
20	12753	14442	20700	10559	761	4438	5258	18354	6411	2581
25	8959	22856	26349	7520	9225	6169	8650	17782	2206	4722
30	12924	11569	33963	13071	18291	10641	2986	6231	4852	7982
35	10111	9414	20748	16658	10253	16629	6571	4242	3300	12151
40	11395	24498	14718	9327	11382	24754	7010	5943	6643	18233

4   Conclusions

A comprehensive study (considering both primary and secondary impact cases at different gait cycles) has been presented in this paper for side and rear impact scenarios in an event of a truck-pedestrian collision to determine the suitability of DEA (Deformable Energy Absorbing) frontal attachments in trucks to improve pedestrian

safety for different impact speeds. It has been observed from the study that for specific gaits, DEA might be a useful alternative in improving pedestrian safety in the case of primary side impact situations but from a holistic viewpoint considering different gait cycles, DEA does not improve pedestrian safety both for side and rear impact situations. Based on MADYMO simulations it has been observed that for primary side impact scenario DEA frontal attachment provides a performance improvement specifically for 0% gait; however, the performance improvement is non-uniform for other gait cycles. For primary rear impact scenarios, it is observed that DEA is not a useful alternative at all. Based on this study it is being reported for the first time that for secondary collision scenarios (involving both side and rear impact cases) DEA is not at all an effective means for performance improvement.

Like all studies, this study is also not without limitation. First of all, the assessments and the conclusions in this study are based on HIC values. Further, experimental investigations are also required in order to verify the numerical findings obtained and presented in this paper. Nonetheless, this investigation shows a direction for new research with both numerical method and a reasonable validation of the model, which demands further exploration before adopting any new pedestrian-safe design for flat fronted trucks.

Acknowledgement

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Appendix A

**Figure A1** Tata SE 1613 Turbo EX BS II truck & truck model developed in MADYMO
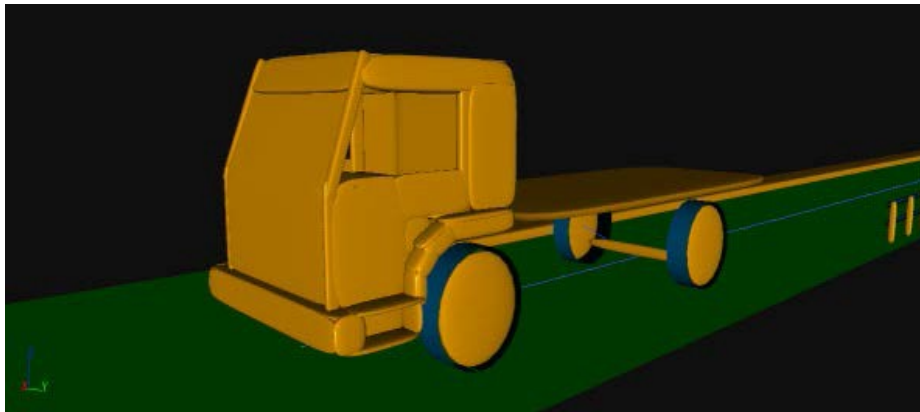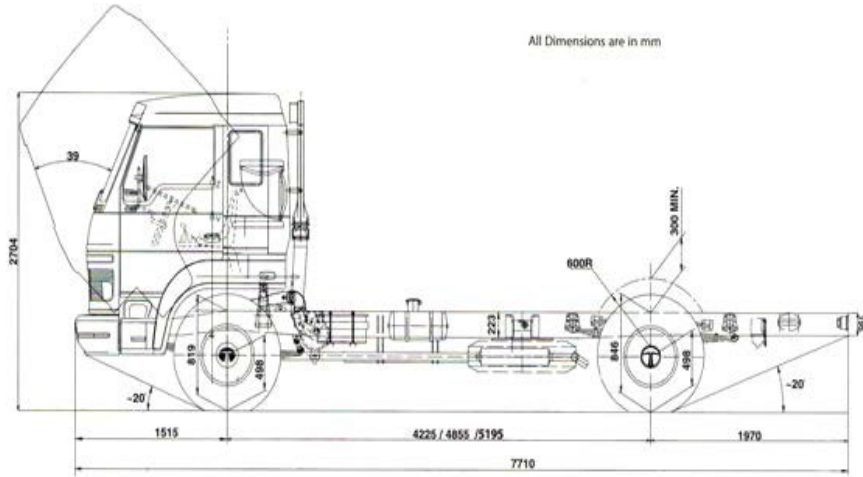
Table A1   Truck part dimension and weights

Max. Permissible GVW/GCW (kg)	*16,200*
Kerb weight with cabin (kg)	4230
Max. Permissible FAW (kg)	6000
Max. Permissible RAW (kg)	10,200
Wheel base (mm)	4225
Max. width (mm)	2316
Max. height (mm)	2704

Figure A2 Gait cycle of pedestrian at time of impact (left to right represent 0%, 10%, 20%, 30% and 40% respectively)
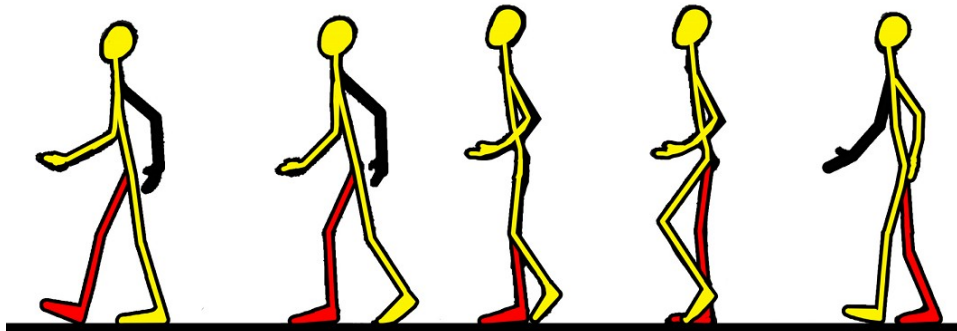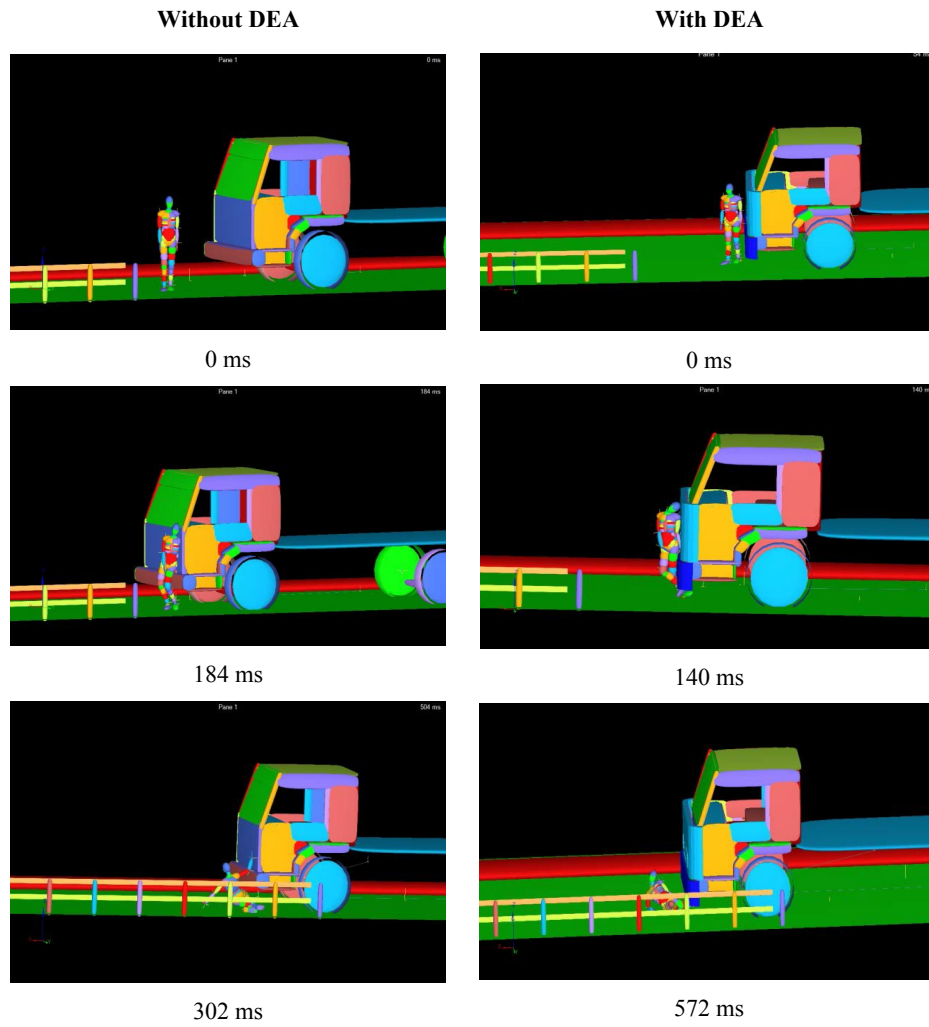

Figure A3 Truck attached with DEA frontal system
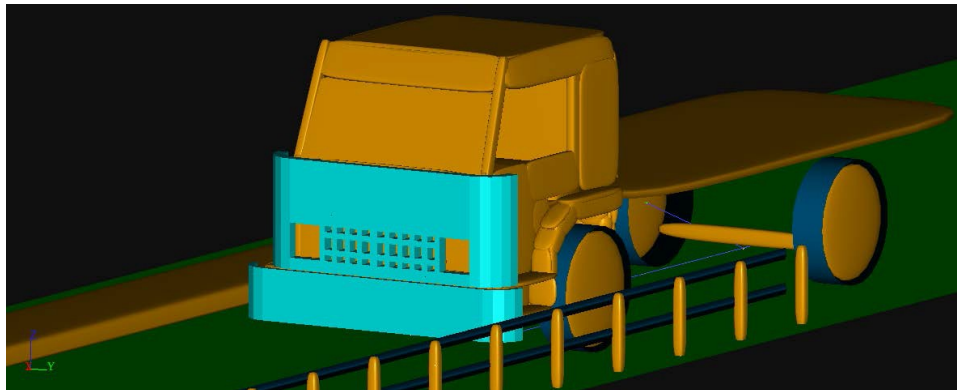
Figure A4 Kinematics of truck-pedestrian side impacts with and without DEA frontal system at 30 kmph

Without DEA   **With DEA**

0 ms   0 ms

184 ms   140 ms

302 ms   572 ms

Figure A5 Kinematics of truck-pedestrian rear impacts with and without DEA frontal system at 30 kmph

Without DEA   **With DEA**

0 ms   0 ms

184 ms   152 ms

520 ms   410 ms

624 ms   688 ms